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Circular design in residential areas: The case of the Vauban Eco-District of Freiburg, Germany

Elifsu Şahin

Department of City and Regional Planning, Faculty of Architecture, İstanbul University, Turkey
Corresponding author: elifsu.sahin@istanbul.edu.tr

Gözde Arzu Sarıcan

Department of City and Regional Planning, Faculty of Architecture, İstanbul University, Turkey

This article examines how circular economy and circular design are interpreted at the scales of urban planning, urban development and urban design, and how they are spatially operationalized through the case of the Vauban Eco-District in Freiburg. Against the deepening unsustainability of the linear “take-make-dispose” model—manifested in the climate crisis, resource scarcity, and escalating waste—the study aims to assess the extent to which circular design principles can be concretized within residential environments. Grounded in an interpretivist epistemology, the qualitative research design integrates a conceptual literature review with an in-depth case study of Vauban. Drawing on existing academic literature, the eight core principles of Circular Urban Design are systematically articulated and used to map Vauban’s practices in energy, water, waste, mobility, green infrastructure, and community governance. The findings indicate that Vauban demonstrates a strong capacity for circularity through closed-loop infrastructural systems and participatory housing production, while also exhibiting limitations related to high costs, insufficient quantitative evidence, and social-justice challenges associated with participatory elitism. The article offers policy lessons on the potentials and conditions of transferability of circular design at the neighbourhood scale.

Keywords: Circular Urban Design, circular economy, circular design, sustainable urbanism, urban regeneration, Vauban Eco-District

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Please cite as: Şahin, E., & Sarıcan, G. A. (2026). Circular design in residential areas: The case of the Vauban Eco-District of Freiburg, Germany. *plaNNext – Next Generation Planning*. Online first (23 August 2026). <https://doi.org/10.24306/plnxt/125>

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Introduction

In the 21st century, the intensifying climate crisis, the accelerating depletion of natural resources, and the environmental pressures generated by urbanization clearly reveal the unsustainability of prevailing production and consumption models (United Nations Environment Programme, 2019; United Nations Human Settlements Programme, 2022; United Nations, n.d.). In this context, the linear economic model based on a “take–use–dispose” logic leads to resource waste, high levels of carbon emissions, and large-scale waste generation (Geissdoerfer et al., 2017). As an alternative to these crises, the circular economy seeks to keep resources in the loop for as long as possible, minimize waste generation, and support the regeneration of natural systems (Avinç & Selçuk, 2024; Ellen MacArthur Foundation, n.d.; Geissdoerfer et al., 2017).

The Ellen MacArthur Foundation (EMF), established in 2013, has played a pivotal role both in shaping the theoretical framework of the circular economy and in defining its fields of application. EMF particularly identifies cities, manufacturing, design, and the fashion sector as key domains for the implementation of circular economy principles. According to EMF, the circular economy is structured around three core principles:

1. Design out waste and pollution
2. Keep products and materials in use
3. Regenerate natural systems

From EMF’s perspective, the circular economy is not confined to production or industry alone; cities and spatial systems are positioned at the very centre of this transformation (Ellen MacArthur Foundation, n.d., 2019a, 2019b).

Circular design offers a holistic design approach that enables products, services, and systems to operate within closed loops from the outset. In this regard, circular design encompasses not only environmental sustainability but also social and economic sustainability principles (Ellen MacArthur Foundation, n.d.; Girard & Nocca, 2019). Circular design has matured through a multidisciplinary evolution, drawing on various intellectual traditions. Approaches such as industrial ecology, regenerative design, cradle to cradle, performance economy, biomimicry, and the blue economy constitute its theoretical foundations (Ellen MacArthur Foundation, 2023; Pieroni et al., 2018; Taşbaşı, 2025). These approaches prioritise the reusability and flexibility of products and buildings, as well as production processes grounded in local resources. In EMF’s definition, circular design aims to prevent waste and pollution, extend material life cycles, and build a sustainable economic and ecological system through systemic transformation (Ellen MacArthur Foundation, 2016). This perspective is particularly crucial in settlement areas characterised by high levels of resource consumption (Bortolotti et al., 2023). The application of circular design in residential environments plays a critical role in securing the sustainability of urban life (Borralló-Jiménez et al., 2020; Bortolotti et al., 2023; Pekdemir et al., 2025). The comprehensive implementation of circular design principles in housing areas, infrastructure systems, energy production, and mobility models can both reduce environmental impacts and contribute to the creation of more liveable cities (Bortolotti et al., 2023; Pekdemir et al., 2025). Long-lasting, flexible, and modular buildings; the widespread use of renewable energy; the establishment of closed loops in water and waste management; and the promotion of social participation provide concrete examples of how circular design can be operationalised at the urban scale (Borralló-Jiménez et al., 2020; Bortolotti et al., 2023; Pekdemir et al., 2025).

The planning process of the Vauban Eco-District in Freiburg, Germany—the focus of this study—does not explicitly employ the term “Circular Design”. However, by holistically organising closed-loop relationships among energy, water, waste, and mobility systems, Vauban concretises the principles of circular design at the spatial scale. Developed through

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the transformation of a former military barracks, Vauban promotes both environmental and social sustainability through local renewable energy production, on-site water management, ecological mobility, material circularity, and community-based housing models. Technical solutions such as local energy generation, rainwater harvesting, and biogas systems are integrated with cooperative housing production and participatory planning processes (Coates, 2013; Fraker, 2013; Medearis & Daseking, 2012; Schroepfer & Hee, 2008). These features render Vauban a laboratory in which circular design is practically internalised.

The rationale for selecting Vauban is not limited to its technical solutions; it also lies in its combined inclusion of governance structures, community participation, and spatial sustainability components. This article therefore approaches Vauban as a multidimensional example of circular urban design. The aim of the research is to assess how circular design principles can be spatialised within residential environments. To this end, Vauban's planning process, governance arrangements, and design strategies are examined through a comparative literature and document analysis based on academic publications, policy documents, and reports. Accordingly, the study seeks to answer the following research questions:

1. How is the concept of circular design defined at the scales of urban planning, urban development and urban design, and through which theoretical approaches is it discussed?
2. Through which instruments and strategies do the Vauban Eco-District demonstrate the feasibility of applying circular design principles at the spatial level?
3. What potentials and limitations do the integration of circular design into urban planning and development policies hold in relation to sustainable urbanisation objectives?

The article first constructs the conceptual framework by discussing the concepts of the circular economy and circular design in the context of the climate crisis and the unsustainability of the linear production-consumption model. It then sets out the qualitative research design, grounded in an interpretivist epistemology and secondary data, and summarises how the conceptual literature review and the qualitative case study of the Vauban Eco-District are structured through existing academic publications and policy documents. The third section addresses the theoretical foundations of circular design and its place in the urban studies literature. It then presents the findings of a VOSviewer-based bibliometric analysis before systematically outlining the core principles of Circular Urban Design (CUD). The fourth section evaluates Vauban's spatial and governance-related circularity capacity by aligning its practices—encompassing energy, water, material flows, mobility, community, and governance cycles—with CUD principles and discusses the limitations of the model through key critiques in the literature. The final section synthesises general conclusions regarding the applicability of circular design at the settlement scale considering the Vauban case and develops policy lessons and suggestions for comparative research to be conducted in different geographical contexts.

Methodology

This research is a conceptual qualitative study grounded in an interpretivist epistemology. This approach assumes that reality cannot be captured as a single, measurable entity; rather, it gains meaning within social, cultural, and spatial contexts (Schwandt, 2000). Accordingly, the study seeks to understand how circular design is interpreted, represented, and spatialised within urban planning, urban development and urban design practices (Creswell & Poth, 2016; Flyvbjerg, 2006; Schwandt, 2000). In this sense, instead of offering a normative assessment, the research adopts an interdisciplinary interpretive analysis that examines how the concept is constructed across different knowledge regimes and how it acquires meaning in relation to urban space (Creswell & Poth, 2016; Flyvbjerg, 2006).

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The study follows a qualitative, multistage research design and is structured around two main methodological components:

- a. Conceptual literature analysis
- b. Qualitative case study

By employing these two methods in combination, the research builds an analytical bridge between the theoretical foundations of circular design and its spatial and governance-related applications in the Vauban Eco-District. The study is based entirely on secondary data; no primary data collection techniques (such as surveys, interviews, or field observations) were used. The data employed were classified into four categories:

- Academic publications: peer-reviewed journal articles, book chapters, and theses.
- Policy documents and planning reports: plans and sustainability reports published by the Municipality of Freiburg, Local Governments for Sustainability (ICLEI), and the Vauban Forum.
- Institutional reports and platforms: publications by the Ellen MacArthur Foundation, UN-Habitat, and UNEP.
- Secondary visual and numerical data: planning schemes and graphical analyses related to energy systems, transport infrastructure, and housing models.

Conceptual literature analysis

In the first stage of the research, a comprehensive conceptual literature analysis was conducted to identify the position, historical development, and conceptual evolution of the term “circular design” within the literature. This stage aimed to examine the interdisciplinary uses of the concept, the diversity of definitions, and its theoretical underpinnings from its emergence to the present. In the second stage, the representation and analytical positioning of circular design within the urban and regional planning literature were examined. For this purpose, an initial search was carried out in the Web of Science (WoS) database using the keyword “circular design”, which was then limited to the categories “Urban Studies” and “Regional & Urban Planning” in line with the aim of the study. As a result of the search conducted in June 2025, 265 academic sources were identified under this planning-specific subcategory. This dataset enabled an analysis of the conceptual diffusion of circular design within the planning discipline, its thematic clusters, and its interdisciplinary intersections. Following the WoS analysis, a second search phase was implemented to examine the concept in a broader and more interdisciplinary context. In this phase, systematic searches were conducted in Scopus, Google Scholar, and ResearchGate. These searches identified an additional set of studies lying outside WoS coverage but intersecting with urban studies, architecture, sustainability, and circular economy fields. In total, 40 studies were selected. This sample was evaluated based on citation count, thematic originality, and relevance to the urban context, and was subsequently subjected to qualitative content analysis.

Qualitative case study – Vauban Eco-District

In the second stage, the Vauban Eco-District was examined using a qualitative case study approach. As defined by Yin (2018) and Stake (1995), qualitative case study research focuses on gaining an in-depth understanding of a phenomenon within its real-life context.

Three site-specific characteristics were decisive in selecting Vauban as the case study area:

1. **Ecological transformation model:** Vauban is a pioneering example of sustainable urban redevelopment that features early, integrated implementations in energy, transport, and water management systems (Medearis & Daseking, 2012; Schroepfer & Hee, 2008).

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2. **Community governance:** The project offers an original model in terms of social capital and governance through participatory planning processes and housing cooperatives (Coates, 2013).
3. **Integration of circular principles:** Due to the integrated design of resource cycles (energy, materials, water, mobility), Vauban provides a suitable context for examining the spatial manifestations of circular design (Fraker, 2013).

During the analysis, academic publications, policy documents, and institutional reports on Vauban were examined using content analysis. These secondary sources—rather than fieldwork—were organised under thematic headings to allow for a holistic assessment of the neighbourhood's spatial, infrastructural, and social arrangements. In this framework, data concerning Vauban's urban form, transport and mobility strategies, green space structure, energy policies and renewable energy applications, water and waste management approaches, and participatory/community processes were analysed systematically.

Each theme was then related to the principles of circular urban design identified in the literature, forming a conceptual evaluative framework. The research questions were designed to jointly address the theoretical framework, the spatial case, and the policy dimension from an integrated perspective, and were systematically aligned with the corresponding methods, as presented in Table 1.

Table 1. Relationship between research questions and methodological approaches. Source: authors

Research question	Methodological approach	Data sources
1. How is the concept of circular design defined at the scales of urban planning, urban development and urban design, and through which theoretical approaches is it discussed?	Discourse-based conceptual literature review; bibliometric thematic mapping using VOSviewer	Academic publications (Pomponi & Moncaster, 2017; Williams, 2019; Bortolotti et al., 2023; Pekdemir et al., 2025, etc.); EMF reports (Ellen MacArthur Foundation, 2013; 2016; 2021; 2023); international reports (UNEP, 2019; UN-Habitat, 2022); Scopus, Web of Science and Google Scholar databases.
2. Through which instruments and strategies does the Vauban Eco-District demonstrate the spatial applicability of circular design principles?	Qualitative case study; thematic content analysis	Qualitative case study (Yin, 2018; Flyvbjerg, 2006; Stake, 1995); thematic content analysis (Creswell & Poth, 2016); participatory planning perspective (Arnstein, 1969; Hamiduddin & Daseking, 2014); regenerative and sustainable neighbourhood lens (Ahern, 2013; Lyle, 1994; Sala Benites et al., 2023).
3. What are the potentials and limitations of integrating circular design into urban planning and development policies for achieving sustainable urbanisation goals?	Policy analysis; analysis of normative planning documents; thematic content analysis	Policy analysis and governance perspective (Bulkeley, 2005; Heurkens & Dąbrowski, 2020; Fratini et al., 2019); critical circular economy literature (Korhonen et al., 2018; Hobson, 2016; Hobson, 2020; Vanhuyse et al., 2021); urban circular assessment frameworks (Papageorgiou et al., 2021; Girard & Nocca, 2019; ICLEI et al., 2021).

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Methodological contributions and limitations

The methodological contribution of this research lies in its integration of a conceptual literature analysis with a qualitative case study, thereby unpacking both the epistemological foundations of the circular design concept and its spatial-practical manifestations. Theoretical debates and applied examples of ecological transformation—which are often treated in isolation in the literature—are brought together within a shared analytical framework through a multistage qualitative design. The study approaches circular design not only as a technical paradigm but also as a mode of social and governance-related production.

The inclusion of the Vauban Eco-District as a qualitative case study has facilitated a deeper understanding of how circular principles are implemented at the urban scale. This analysis organised around themes such as energy, materials, water, and social cycles, enables a discussion of the spatial and governance dimensions of the concept.

The research also has several limitations. First, it relies exclusively on secondary data and does not employ primary data collection methods (such as interviews or field observations). This constrains the depth of analysis that can be offered regarding Vauban's current governance processes and actor interactions. In addition, due to the categorical structures of the databases used and language-related constraints, certain local or grey literature sources may have remained outside the scope of the study.

Use of Artificial Intelligence (AI)

During the preparation of this article, the generative artificial intelligence (AI) tool ChatGPT (OpenAI) was used as a supportive tool for language editing, improving academic phrasing, clarity, and readability, as well as for creating some of the visuals used in the study and enhancing their visual presentation. AI tools were not used to generate research data, conduct data analysis, develop the methodological framework, interpret the findings, or generate references. All AI-assisted textual and visual outputs were critically reviewed, verified, and, where necessary, revised by the authors. The authors retain full responsibility for the scientific accuracy, originality, interpretations, and final content of the article.

Circular design

The linear economy is the traditional production and consumption system based on a “take-usedispose” model (Ellen MacArthur Foundation, 2021; Geissdoerfer et al., 2017). Resources are extracted from nature, products are manufactured, used, and ultimately become waste. Yet increasing resource scarcity, biodiversity loss and economic crises have gradually undermined the sustainability of the linear economy. In contrast to the linear model, which rapidly depletes resources and generates large volumes of waste, the circular economy seeks to revalorise these resources within the system and establish a sustainable cycle of production and consumption (Ellen MacArthur Foundation, 2013; Ellen MacArthur Foundation, 2019a; Geissdoerfer et al., 2017; Korhonen et al., 2018).

In this context, the circular economy, originally conceptualised by David Pearce and R. Kerry Turner, is a sustainable model that aims to keep resources within the system for as long as possible and to minimise waste through reuse, repair, recycling and energy efficiency. In this system, waste is treated as a resource for new production processes; while biological materials are returned to nature, technical materials are reprocessed and reintegrated into the economy. The overarching aim is to increase resource efficiency and thereby secure environmental and economic sustainability (Heshmati, 2015; Murray et al., 2017; Pearce & Turner, 1990). The implementation of the circular economy is directly linked to other sustainability objectives such as the adoption of clean production technologies, strengthening

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producer and consumer responsibility, the development of sharing-based product and service platforms, and the wider use of renewable energy and materials (Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016; Lewandowski, 2016). With its promise to decouple economic growth from resource consumption and to create employment even in times of crisis, the circular economy has come to occupy a central position on business and policy agendas in recent years.

Despite the fact that many European city governments have recently turned to implementing circular economy principles at the urban scale—and the concept has gained visibility in urban policy discourses—research on the “circular city” is still at a relatively early stage (Hobson, 2016; Marin & De Meulder, 2018; Pomponi & Moncaster, 2017; Prendeville et al., 2018). Studies on the circular economy have predominantly focused on technological and market-based solutions (Bulkeley, 2005; Gregson et al., 2015; Murray et al., 2017), paying comparatively less attention to how governance arrangements and local specificities promote or hinder resource circularity. Moreover, debates on the socio-spatial outcomes of different forms of circularity remain limited (Bortolotti et al., 2023; Fratini et al., 2019; Heurkens & Dąbrowski, 2020; Hobson, 2020).

The circular design approach is shaped by the concept of the circular economy, which seeks the sustainable use of resources and the minimisation of waste generation (Moreno et al., 2016). Within the circular economy, the design process emerges as a holistic field of intervention that encompasses the entire life cycle of a product, rather than addressing only post-production stages (Bocken et al., 2016; Ellen MacArthur Foundation, 2021; Geissdoerfer et al., 2017). Circular design refers to an approach to product, service and system design that aims to keep resources in use for as long as possible, minimise waste generation and support the regeneration of natural systems (Bocken et al., 2016; Ellen MacArthur Foundation, 2021; Moreno et al., 2016). This approach rests on core design principles such as durability, reparability and recyclability to operationalise the circular economy (Bocken et al., 2016; Moreno et al., 2016).

The Circular Design Guide developed by the Ellen MacArthur Foundation and IDEO structures the circular design process around four main phases: “understand”, “define”, “make” and “launch”. The first phase, “understand”, aims to build an understanding of circular thinking and design solutions; the second phase, “define”, focuses on identifying circularity potentials and setting goals; the third phase, “make”, centres on understanding user needs, generating creative ideas and developing prototypes; and the final phase, “launch”, involves bringing products and services to the market and collecting feedback (Ellen MacArthur Foundation & IDEO, 2017). Through this approach, the adoption of environmentally friendly and sustainable production–consumption models, the reduction of waste and the more efficient use of resources are targeted.

Although ideas related to reuse, waste reduction and the regeneration of natural systems have existed for a long time, systematic debates on the concept of circular design have largely emerged since the late twentieth century. Drawing on different intellectual traditions, circular design and circular economy approaches (Table 2) bring together various principles and theoretical frameworks. From the 1970s onwards, John T. Lyle’s (1994) “regenerative design” approach argued that all human-made systems should be designed as structures that continuously restore and renew resources, energy and materials. The “industrial ecology” approach, which analyses material and energy flows in industrial systems and proposes that the waste output of one process can serve as the input of another, reached a critical milestone with Frosch and Gallopoulos’s (1989) notion of “industrial ecosystems”. From the 1980s onwards, Walter Stahel’s (2010) “performance economy” model advocated extending product lifespans, promoting reuse and developing service-based business models to reduce resource consumption and waste.

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In the early 2000s, the “cradle to cradle” approach developed by Michael Braungart and William McDonough gained prominence, emphasising the design of products as continuous cycles of biological nutrients and technical components and thus reinforcing the idea of closed systems (McDonough & Braungart, 2002). Another approach inspired by natural systems, “biomimicry”, is based on emulating nature’s regenerative processes and closed-loop models. In this vein, Gunter Pauli’s (2010) “blue economy” model aims to reconfigure sustainable business models in line with local resources and natural processes, taking biomimicry as its starting point.

Table 2. *The evolving theoretical framework of the circular design approach. Source: authors*

Period	School of thought	Key proponent	Key contribution
1970s–1980s	Regenerative design	John T. Lyle	Systems that restore and regenerate resources
1980s	Industrial ecology	Frosch & Gallopoulos	Industrial ecosystems and resource cycling
1980s–present	Performance economy	Walter Stahel	Product life extension and service-based business models
1990s–2000s	Cradle to cradle	Braungart & McDonough	Design for continuous material cycles
1990s–present	Biomimicry	Janine Benyus & others	Closed-loop design inspired by nature
2010	Blue economy	Gunter Pauli	Use of local resources and systemic innovation

The bibliometric analysis of the academic publications retrieved from the Web of Science database using the keyword “circular design” is presented in Figure 1. The search was limited to the categories “Urban Studies” and “Regional & Urban Planning”, yielding a total of 265 sources. Terms that appeared at least five times in this corpus were analysed with the VOSviewer software. Figure 1 illustrates the co-occurrence relationships among the most frequently used terms and the intensity of these relationships. Each node in the network diagram represents a term frequently used in the literature, while node size indicates the frequency of occurrence of that term. The links between nodes reflect the level of co-occurrence between concepts, that is, how often they appear together. The colour scale in the visualisation shows the temporal distribution of keywords in the literature: purple tones represent earlier studies, whereas yellow tones denote the most recent publications. This network map reveals thematic clusters that can be directly associated with the eight core principles of Circular Urban Design (CUD).

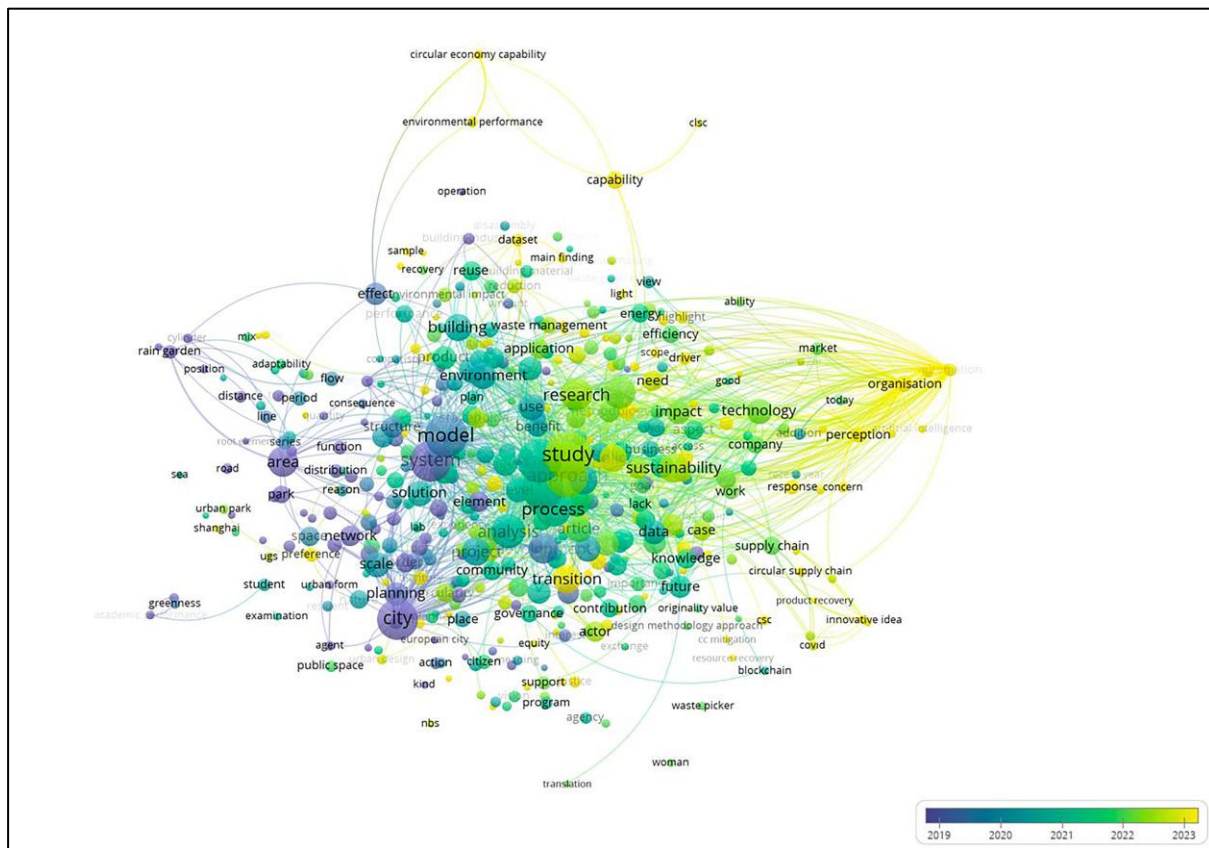


Figure 1. Bibliometric co-occurrence network of publications on “circular design” (Web of Science, Urban Studies & Regional & Urban Planning, $n = 265$). Source: authors’ elaboration of VOSviewer results

On the map, clusters around terms such as “waste management”, “reuse”, “recycling”, “building material”, “construction waste” and “environmental performance” are directly related to the principle of Material Circulation and Resource Management. These keywords represent studies focusing on material circularity, waste management and resource recovery. This area is linked to sub-themes such as environmental engineering, circularity in the construction sector and life-cycle assessment of materials. The purple–blue cluster where terms such as “urban area”, “planning”, “city”, “public space”, “regeneration” and “adaptive reuse” are concentrated corresponds to the principle of Circulation and Reuse of Spaces. This cluster reflects research on the transformation of underused spaces, strategies of adaptive reuse and the production of spatial circular value.

The green-toned sub-cluster in which concepts such as “adaptability”, “transition”, “resilience” and “flexibility” co-occur represents studies focusing on Adaptability and Flexibility, that is, the capacity of buildings and spaces to respond to changing needs over time. This area is associated with modular housing systems, flexible planning and temporary uses of space. The central zone, where “community”, “equity”, “social sustainability”, “transition” and “planning” are clustered, represents the interaction of social, spatial and material processes. This cluster overlaps with the CUD principle structured around social justice, participation, spatial equality and social sustainability.

On the left side of the map, terms such as “rain garden”, “NBS (nature-based solutions)”, “green infrastructure”, “ecosystem services”, “urban park” and “environment” form the

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bibliometric reflection of the principle of Regeneration through Natural Processes. These clusters are frequently emphasised in studies exploring the role of nature-based solutions, green infrastructure systems and ecological regeneration in circular urbanisation. At the centre of the map, the broad green core formed by “sustainability”, “system”, “process”, “model”, “analysis” and “transition” points to research that addresses environmental, economic, social and institutional dimensions within an integrated systems perspective. This core is directly related to the CUD principle of Multidimensional Integration.

In the yellow cluster on the right, terms such as “organisation”, “management”, “knowledge”, “policy”, “governance” and “stakeholder” represent the emerging literature on multiactor governance and knowledge-sharing networks. This cluster reflects stakeholder-oriented circularity debates that have intensified particularly after 2021. Here, the corresponding CUD principle is Stakeholder Participation and Governance. In the yellow-green cluster at the lower right, represented by terms such as “supply chain”, “circular supply chain”, “technology”, “innovation”, “market” and “company”, the focus is on Integration of Local and Global Dynamics, highlighting the links between global production–consumption chains and local circular strategies. This area marks the concentration of debates on the spatial embedding of the circular economy and on local-global interactions.

Overall, the circular urban design literature is evolving towards a more holistic, systems-oriented and governance-focused direction. Examining the colour distribution, one can observe that 2019–2020 (purple) is dominated by spatial and ecological themes such as “city”, “planning”, “green infrastructure” and “reuse”; 2021–2022 (green) foregrounds theoretical and methodological notions such as “transition”, “model”, “system” and “process”; and 2023 onwards (yellow) highlights governance and digital transformation themes such as “organisation”, “technology”, “supply chain” and “innovation”. Thus, Figure 1 demonstrates that the core principles of circular urban design are networked with one another, and that the thematic evolution of the literature has expanded from environmental circularity towards social and governance-related integration.

Circular urban design

The projection that the global urban population will rise from 55 % in 2025 to around 70 % by 2050, with approximately 2.5 billion new residents added to cities in this period (World Bank, 2021), makes the challenges facing urban systems increasingly complex in the context of the Sustainable Development Goals. These challenges include multidimensional processes such as managing resource scarcity, reducing carbon emissions, controlling sprawling urbanisation, addressing social inequalities, and ensuring resilience to climate change and demographic transformations (Dodman et al., 2017; Li et al., 2025). Although sustainability now occupies a central place in urban planning discourse, existing approaches often treat environmental, social and economic dimensions in isolation, which limits their capacity to generate holistic solutions (Gallotti et al., 2021).

In this context, Circular Urban Design (CUD) emerges as an innovative planning approach that addresses social, spatial and material interactions in cities from an integrated perspective and translates circular economy principles into concrete spatial and governance practices (Böhm & Alexander, 2024; Loukaitou-Sideris, 2012; Pekdemir et al., 2025). CUD is particularly notable for its applicability at neighbourhood and district scales, opening debate on how these intermediate scales operate between individual buildings and the city (Amenta et al., 2022; Elshater & Abusaada, 2022; Tapia et al., 2021; Verga & Khan, 2022). Where urban planning sets the overarching policy framework, urban design becomes a critical instrument that translates circularity into spatial arrangements and resource management strategies (Munonye & Ajonye, 2024; Tucci et al., 2021).

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At the urban scale, the application of circular design principles plays a decisive role in enhancing the environmental, economic and social resilience of cities. Energy and resource efficiency, together with effective waste management, are among the key criteria for building sustainable cities (Söderström et al., 2014); in settlements where these principles are implemented, energy consumption decreases, waste generation is reduced and the effective lifespan of natural resources is extended (Bocken et al., 2016). Circular urban design is therefore understood as a multidimensional approach that supports not only environmental sustainability but also social well-being and economic efficiency. According to the literature, the theoretical framework of circular urban design is shaped around several core principles outlined in the next subsections.

Regeneration through natural processes

One of the fundamental principles of CUD is regeneration through natural processes. Integrating natural systems with the city means reactivating nature's circular capacity (Jacintos Nieves & Delgado Ramos, 2023; Pelorosso et al., 2017; Verga & Khan, 2022; Williams, 2020). Within this framework, nature-based solutions, green infrastructure, greywater recycling and the incorporation of ecosystem services into planning processes come to the fore (Ahern, 2013; Beatley, 2011).

Material circulation and resource management

Material circulation within cities—through the reuse of resources, minimisation of waste and extension of the lifespan of existing buildings—constitutes a key objective of circular urbanisation (Bortolotti et al., 2023; Domenech & Borrion, 2022; Krysovaty et al., 2018; Lakatos et al., 2021; McNeill, 2022). In the construction sector, practices of recycling and reuse play a crucial role in making cities more circular (Brglez et al., 2024; Marin et al., 2020; Foster & Saleh, 2021). In this regard, Bocken et al. (2016) show that adaptive reuse of buildings can generate savings in both materials and energy, while Pomponi and Moncaster (2017) emphasise that such processes are critical for reducing the carbon footprint.

Circulation and reuse of spaces

At the spatial level, circulation of spaces within CUD encompasses the transformation of underused areas, the reintegration of abandoned zones into the city, and the enhancement of spatial efficiency (Amenta & van Timmeren, 2018; Della Spina & Giorno, 2022; Williams, 2019).

Adaptability and flexibility

The principle of adaptability strengthens the spatial resilience of CUD through flexible urban strategies, modular design, temporary uses and approaches to adaptive reuse (Gravagnuolo et al., 2019; Sala Benites et al., 2023; Wuyts et al., 2022). Brand (1994) argues that the built environment should be conceived as a “learning organism” that evolves over time, while Schneider and Till (2005) demonstrate that flexible housing typologies enhance the sustainability of the housing stock.

Socio-spatial-material interaction

This principle concerns the analysis of multilayered relationships between social structures, spatial forms and material processes (Calisto Friant et al., 2023; Hobson, 2020; Vanhuyse et al., 2021; Vanhuyse et al., 2021). Anttiroiko (2023), and Wildeboer and Savini (2022) argue that space constitutes an infrastructure that channels material flows, whereas Verga and Khan

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(2022) highlight the necessity of integrating social justice into circularity policies. In this way, the circular city is conceptualised not only as a system of technical infrastructures but also as a system in which social equality and spatial justice are reproduced.

Multidimensional integration

Papageorgiou et al. (2021), and Girard and Nocca (2019) stress that economic, environmental, social, cultural and governance dimensions in circular urbanism should not be treated as separate spheres but as mutually reinforcing systems. This approach reveals that circular cities represent not merely a technical transformation but also a process of institutional and cultural restructuring.

Stakeholder participation and governance

Multilevel, transparent and equitable collaborations among the public sector, private actors, local communities and technical experts enhance both the legitimacy and feasibility of circularity initiatives (Anttiroiko, 2023; Florez Ayala et al., 2022; Girard & Nocca, 2019; Langergraber et al., 2021). Arnstein's (1969) "ladder of citizen participation" and Healey's (1997) collaborative planning perspective provide the theoretical foundations for this governance transformation.

Integration of local and global dynamics

This principle aims to balance local resource cycles with global production-consumption systems. Florez Ayala et al. (2022), and Marin and De Meulder (2018) argue that global supply chains may undermine the circular capacity of cities, and therefore local production and resource use should be prioritised.

In addition to these clearly defined core components of CUD, the literature frequently highlights several complementary principles:

- Life-cycle approach: involves circular assessments that cover all life stages of buildings (Gomes et al., 2022; Sala Benites et al., 2023).
- Spatial circular actions: define different typologies of circular behaviours and interventions in space (Ancapi, 2023; Williams, 2021).
- Multiscalar approach: requires simultaneous circular practices at building, neighbourhood and city scales (Wuyts & Marin, 2022).
- Restorative approach: advocates the inclusion of cultural heritage in renewal processes while preserving its values (Foster & Saleh, 2021).

Overall, circular urban design is not merely a technical or physical tool of transformation; it constitutes a holistic paradigm of socio-spatial, environmental and institutional restructuring. The principles on which Circular Urban Design (CUD) is based—regeneration through natural processes, material circulation and resource management, circulation and reuse of spaces, adaptability and flexibility, socio-spatial-material interaction, multidimensional integration, stakeholder participation and governance, and the integration of local and global dynamics—form the key building blocks of cities' sustainable futures. This integrated approach positions cities not simply as energy-efficient or waste-reducing systems, but as living organisms that learn, adapt and reproduce their own resource cycles. Consequently, achieving sustainability depends not only on technical solutions but on the simultaneous realisation of social, spatial and material transformations.

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Circular urban design practices in Vauban

Located in southern Germany with a population of around 220,000, the city of Freiburg lies close to the Swiss and French borders (Figure 2). As a historic university town, its GDP per capita is about 11 % above the European average (Fraker, 2013; Fastenrath & Preller, 2018). Freiburg is also the German city with the highest solar radiation, receiving more than 1,700 hours of sunshine per year. Owing to this high solar potential, Freiburg has been characterised as a “solar region” and, with its environmental policies and renewable energy initiatives, has long been one of the pioneer cities of the German environmental movement (Fraker, 2013; Fastenrath & Preller, 2018).

Vauban, a mixed-use neighbourhood situated three kilometres southwest of the city centre (Figure 2), is one of the exemplary projects of sustainable urban design. After 85 % of Freiburg’s historic centre was destroyed during the First World War, the foundations for the city’s post-war spatial and settlement development were laid. From the 1950s onwards, a reconstruction process oriented towards sustainable development was initiated, with particular attention to the traditional urban fabric and cultural heritage. In the 1960s the tram network played a crucial role in Freiburg’s urban development and expansion. The “five fingers” concept, adopted to distinguish built-up areas from open spaces and to guide the distribution of green areas, shaped the city’s growth. Pedestrianisation policies in Freiburg date back to 1949 (Fraker, 2013; Fastenrath & Preller, 2018).

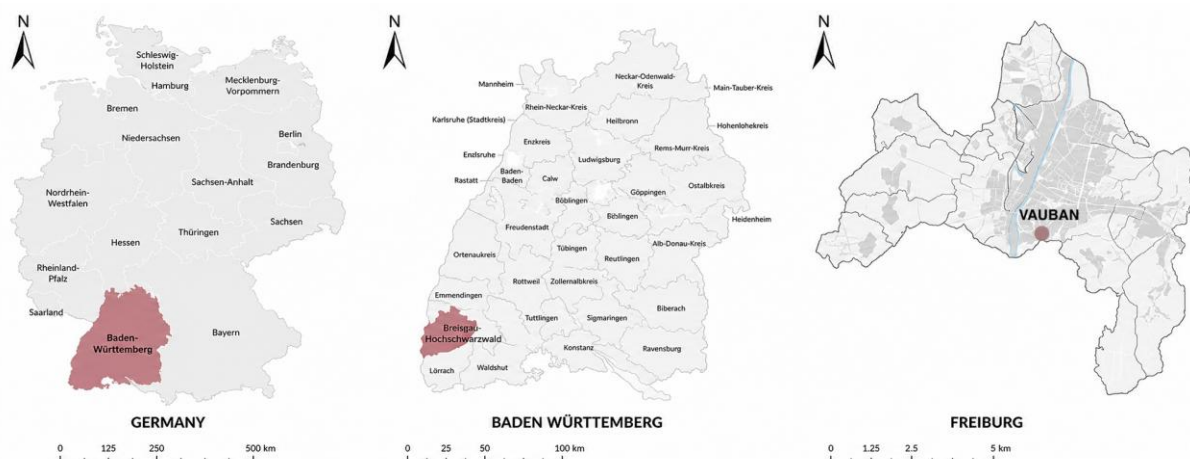


Figure 2. Location of Freiburg and the Vauban Eco-District in Germany. Source: Created by the authors using OpenStreetMap. AI-assisted visualisation was used in preparing this figure.

In Vauban’s mobility system, walking, cycling, light-rail transit and car-sharing schemes are prioritised over private car ownership, promoting healthier and more sustainable modes of movement. The broader transport strategy in Freiburg aims to provide viable alternatives to car use, prevent car dependency and urban sprawl, and regulate land use. Approximately two-thirds of the municipality consists of green areas: forests account for 42 % of the territory, while 27 % is used for agriculture, recreation and water protection. Resource conservation is a key principle in Freiburg’s planning process, and Vauban has been developed in line with this perspective. A broad and participatory civic base has been decisive in building consensus among the main stakeholders around the city’s sustainable development agenda (Coates, 2013; Fraker, 2013).

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In 1993, the City of Freiburg initiated the transformation of a 42-hectare former French military barracks in Vauban, taking a key role as both landowner and planning authority (Fraker, 2013; Fastenrath & Preller, 2018). The main objective of the project was to create a mixed-income residential district for approximately 5,000 inhabitants and around 600 jobs (Fraker, 2013; Fastenrath & Preller, 2018). Rather than a purely physical transformation, Vauban represents an innovative transformation model that integrates social, economic and ecological goals shaped through participatory processes. One of the guiding principles of this process was the notion of “learning while planning”. A 1994 urban design competition gathered community-based ideas, and the development plan was grounded in this participatory process (Coates, 2013; Fraker, 2013; Hamiduddin & Daseking, 2014).

The citizens’ initiative Forum Vauban, officially established in 1995, coordinated this process and played a decisive role in defining ecological design criteria, promoting the Baugruppen (building groups) model, and implementing car-free living schemes instead of individual car ownership. Forum Vauban brought together future property owners and supported them in collectively planning their buildings through construction cooperatives. It also encouraged compliance with environmental standards regarding energy efficiency, waste management and public transport (Fastenrath & Preller, 2018; Hamiduddin, 2015; Hamiduddin & Daseking, 2014). Within the project, land parcels in Vauban were subdivided into smaller lots and sold directly to user groups, which reduced costs by eliminating intermediary developers and opened the way for participatory construction models. Forum Vauban was financed through public subsidies, membership fees and donations, and through social-cultural activities such as publishing a neighbourhood magazine, organising local markets and establishing a community centre (Fraker, 2013; Fastenrath & Preller, 2018; Hamiduddin, 2015; Hamiduddin & Daseking, 2014). Over time, the initiative contributed not only to planning processes but also to the strengthening of community life. The success of the project was facilitated by the political support of the City of Freiburg, transparent governance procedures and the innovative approaches of key actors such as chief planner Sven von Ungern (Coates, 2013; Fraker, 2013; Schuetze, 2018).

Vauban’s urban form

Although explicit goals for the urban form of Vauban were not formally defined, its physical structure was shaped by the principles emerging from the open competition of the 1990s and by Freiburg’s planning guidelines (Coates, 2013; Fraker, 2013). These principles provided a flexible framework that directed individual developments on small plots. Vauban’s urban form can be described as a “T”-shaped structure created by public spaces (Coates, 2013; Fraker, 2013). The top of the “T” is formed by an avenue at the eastern entrance, with commercial uses on the ground floor and energy-efficient residential buildings incorporating rooftop photovoltaic systems above (Hamiduddin, 2015; Hamiduddin & Daseking, 2014). This commercial street serves as the main axis connecting Vauban both to the city centre and to the regional transport network. The stem of the “T” is a green spine running east–west. This linear open space is a hybrid public realm integrating two-way traffic, a tram line and stormwater channels. It simultaneously functions as a linear park, a public transport corridor and an urban boulevard (Hamiduddin, 2015; Hamiduddin & Daseking, 2014). Most buildings are positioned perpendicular to the green spine, with only their narrow facades facing it, thus ensuring visual and physical permeability into the inner spaces of the blocks. Defined public open spaces are located on both sides of the spine. Three tram stops are placed along this axis, each surrounded by local shopping facilities (Coates, 2013; Fraker, 2013; Hamiduddin & Daseking, 2014). On the northern side of the spine, roughly one third of its length, a community square is framed by a south-facing building that houses the Forum Vauban offices, a restaurant, meeting rooms and a small guesthouse. This space has been designed as a social

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meeting point for neighbourhood residents. In the southern part of Vauban, “U”-shaped streets provide access to the Baugruppen housing, while the northern part features a three-layered street structure (Coates, 2013; Fraker, 2013). The first layer again consists of “U”-shaped access streets, while the other two layers employ a more conventional street-and-block pattern with discontinuous streets; some change direction at each block, others end in cul-de-sacs. As a result, motorised traffic is fragmented, whereas pedestrians and cyclists enjoy a continuous and prioritised network (Coates, 2013; Fraker, 2013).

Mobility and transport in Vauban

While Vauban is based on the principles of traditional transit-oriented development, it goes beyond this framework to become one of the first projects in Germany to implement the concept of “car-free living” in a comprehensive manner. The aim was not merely to create a small car-free zone, but to reduce car use across the entire neighbourhood and generate environmental and social benefits. The main transport goals can be summarised as follows:

- Priority is given to pedestrians, cyclists and public transport users.
- Schools, workplaces, shopping facilities and social amenities are located within a ten-minute walking or cycling distance from all residential areas.
- Parking in front of homes is not permitted; only short-term stopping for loading and unloading is allowed. Cars are directed to multistorey car parks located on the periphery of the neighbourhood.
- Speed limits in residential streets are restricted to “walking speed” (5–8 km/h), while main axes are limited to 30 km/h.
- Car-sharing schemes are actively supported within the community.

A strong public transport network is provided through tram and bus lines. According to the development plan, the construction of private parking on individually owned plots was prohibited, and parking demand was to be met solely by peripheral car parks. Residents who joined the car-sharing programme were offered a free public transport pass for one year. While a continuous network was created for pedestrians and cyclists, motorised traffic was channelled into a limited and fragmented street system.

The main public transport spine is a tram line running along the central park boulevard, passing within a maximum of 300 metres of each dwelling. The line connects Vauban to the city centre in approximately ten minutes, with trams running every eight minutes. Regional bus routes are integrated with the tram line (Coates, 2013; Fraker, 2013). Although no official travel behaviour survey has been conducted, the presence of a primary school, kindergartens, supermarkets, workplaces, and social facilities within the neighbourhood has effectively turned Vauban into a “short-distance neighbourhood (Coates, 2013; Fraker, 2013; Gössling et al., 2016). Around 70 % of households do not own a private car. This reduces the car ownership rate to around 250 vehicles per 1,000 residents—about one-third of the national average—and means that only 10–15 % of daily trips are made by car, compared with roughly 50 % in Germany as a whole (Fraker, 2013; Gössling et al., 2016).

Green spaces in Vauban

Despite the relatively high residential density—exceeding 30 units per hectare—the neighbourhood features a richly vegetated urban fabric owing to the landscape strategies applied throughout the project (Coates, 2013; Fraker, 2013). Along the central park-boulevard spine, the tram runs on grass tracks rather than asphalt, mature trees are preserved, and the line is left unfenced, thereby creating a permeable open space. Together with the stormwater channel, this linear green area provides continuity along the tram route, functioning both as a

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transport corridor and as an ecological linkage (Coates, 2013; Fraker, 2013; Gössling et al., 2016).

Three green spaces intersect the main spine, connecting the neighbourhood in a north–south direction and facilitating access to the ecologically restored Sankt-Georgen stream biotope on the southern edge (Coates, 2013; Fraker, 2013). Vertical greening on many building facades provides shade and cooling in summer as well as aesthetic benefits. More than half of the buildings are equipped with green roofs, which combine insulation, rainwater retention and renewable energy production functions (Fraker, 2013; Gössling et al., 2016).

Energy policies and renewable energy applications

Energy strategies in Vauban are grounded in national and local policies for energy efficiency and sustainability. At the neighbourhood scale, low energy consumption, climate-responsive passive design principles and local renewable energy generation are key objectives. The basic standard for energy use limits annual heating energy consumption to a maximum of 65 kWh/m²/year (Fraker, 2013; Gössling et al., 2016).

In Baugruppen projects, solar thermal collectors and photovoltaic systems have been installed to utilise solar energy for both hot water and electricity production (Coates, 2013; Fraker, 2013). The largest panels are located on solar car parks and in the Solarsiedlung (Solar Settlement) quarter. More than 100 dwellings meet the “passive house” standard, and 75 units have been built as “plus-energy houses”, feeding back around 15 % of their annual energy consumption to the grid. Some buildings in the area have approached the “zero-energy” target. Together, these systems meet 100 % of heating demand and 60 % of electricity demand. Overall, about 93 % of Vauban’s total energy needs are supplied from renewable sources (Fraker, 2013).

Water management

Water management in Vauban has evolved not through strong central targets but through local initiatives and innovative practices developed by Baugruppen. Guided by Forum Vauban, solutions such as rainwater harvesting, vacuum toilet systems and biogas production from wastewater have been implemented. The settlement plan aims to infiltrate 90% of rainwater into the soil and is supported by green roofs and permeable surfaces (Fraker, 2013; Gössling et al., 2016). Instead of conventional infrastructure, simple infiltration ditches were adopted, reducing surface runoff and recharging groundwater. Although quantitative data are limited, existing studies suggest that the system functions effectively. This experience illustrates that ecological sustainability can be achieved through local and participatory initiatives even in the absence of strict central regulation (Coates, 2013; Fraker, 2013).

Waste management

There were no centrally defined targets for waste management in the Vauban project. Strategies for waste reduction, recycling and reuse were developed by the Baugruppen in line with their own project goals (Coates, 2013; Fraker, 2013). Educational and awareness-raising activities conducted by Forum Vauban on sustainable construction and lifestyles contributed to the widespread adoption of ecological waste practices across the neighbourhood. With the support of Forum Vauban, informational leaflets on reducing and recycling construction waste were distributed to developers, and recycling stations were established to separate and collect scrap metal and construction remains (Coates, 2013; Fraker, 2013; Gössling et al., 2016). Regular household waste collection and recycling services are provided by the City of Freiburg. However, no quantified data have been reported on the effectiveness of recycling

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stations or information campaigns in reducing construction waste during the construction phase (Coates, 2013; Fraker, 2013). Likewise, detailed statistics on municipal household waste collection and recycling have not been made available specifically for Vauban. Overall, waste management in Vauban has been shaped less by centralised planning and more by local initiatives, particularly through awareness-raising and structural measures aimed at reducing waste generation during the construction process (Fraker, 2013; Gössling et al., 2016).

Participatory and community processes

From the outset, one of the core social objectives of the Vauban project was to bring together legal, political, social and economic actors from the bottom up, and in particular to involve future residents in the planning process. Two main goals were defined: (1) to create a diverse community in which different lifestyles can coexist, and (2) to enable people from various social groups to become homeowners. Social and cultural programmes developed in line with these aims include the balanced distribution of living and working spaces, social diversity, a mixed-use neighbourhood centre that meets daily needs, a primary school and kindergartens, family- and child-friendly public space design, a community house and a weekly farmers' market (Coates, 2013; Fraker, 2013). The most influential mechanism in realising these goals has been the establishment of building collectives known as Baugruppen. These collectives purchased designated plots directly and designed and built their own housing (Gössling et al., 2016; Hamiduddin, 2015).

Forum Vauban supported this process both technically and organisationally, enhancing participation through public communication, the neighbourhood magazine *Vauban Actuel*, meetings and events (Coates, 2013; Fraker, 2013). The participatory planning approach played a critical role not only in achieving energy efficiency and renewable energy targets but also in realising social objectives such as social integration, age-friendly living environments and family-oriented public space design (Fraker, 2013; Gössling et al., 2016; Hamiduddin, 2015; Hamiduddin & Daseking, 2014). With initial funding from the municipal and federal levels, Forum Vauban acquired legal status, which helped institutionalise the process. Subdividing plots into small units and selling them directly to Baugruppen increased housing affordability by eliminating intermediary developers (Coates, 2013; Fraker, 2013). This approach strengthened social ties and collective attachment and provided a basis for innovative practices such as car-free living and child- and age-friendly environmental design, all co-produced with community participation (Coates, 2013; Fraker, 2013).

Ten former barracks buildings were converted into student residences accommodating 600 students with low income. The Self-Organised Independent Settlement Initiative (SUSI) project has offered affordable and alternative cooperative housing options (Fraker, 2013; Gössling et al., 2016; Hamiduddin, 2015; Hamiduddin & Daseking, 2014). The transformation of the area has been shaped around criteria of sustainability, spatial integration and social equity. Over time, social organisations have become embedded in neighbourhood culture, expanding to include communal meals, annual festivals, flea markets, children's cinema events, art and music classes, sports tournaments and fundraising activities (Coates, 2013; Fraker, 2013). These practices have turned Vauban into an integrated community that is socially diverse, family-friendly and welcoming to older residents (Coates, 2013; Schuetze, 2018).

Table 3 systematically matches the components of the Vauban neighbourhood—its spatial structure, transport policies, energy and water management, green infrastructure, community organisation processes and cooperative housing production model—with the eight core principles of Circular Urban Design (CUD) identified in the literature. Each CUD principle finds

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concrete expression in Vauban: the innovative strategies implemented in the neighbourhood form an integrated pattern of circular urbanism, ranging from regeneration through natural processes to stakeholder participation, and from local resource cycles to spatial flexibility. In this sense, the table makes Vauban's relationship with the theoretical framework of CUD visible in a clear and comparative way, providing both an analytical classification and a conceptual assessment.

Table 3. *Systematic alignment of practices in the Vauban Eco-District with the principles of Circular Urban Design (CUD). Sources: Coates, 2013; Fraker, 2013; Gössling et al., 2016; Hamiduddin, 2015; Hamiduddin & Daseking, 2014; Schroepfer & Hee, 2008; Schuetze, 2018.*

CUD principle	Practices in the Vauban Eco-District
1. Regeneration through natural processes	• Grass-covered tram line and a fully permeable open space design • Ecological corridor created by the combination of the stormwater channel and the tram line • Ecological restoration of the Sankt-Georgen stream biotope and its integration with the neighbourhood • Green roof systems installed on more than half of the buildings (providing insulation, rainwater retention and renewable energy generation) • Vertical greening on building facades (cooling microclimate effects and aesthetic enhancement)
2. Material circulation and resource management	• Recycling stations installed during the construction phase, enabling the separation of scrap metal and construction waste • Material reduction and reuse strategies developed by the Baugruppen • Closing the energy loop (e.g. photovoltaic panels, solar collectors and plus-energy houses) • Around 93 % of the neighbourhood's energy demand being met from renewable sources
3. Circulation and reuse of spaces	• Conversion of former barracks buildings into student dormitories accommodating 600 residents • Production of alternative housing in repurposed buildings by the SUSI cooperative • Creation of the T-shaped urban form through the reorganisation of the existing physical infrastructure • Integration of mixed-use centres that ensure short-distance accessibility into the pre-existing building fabric
4. Adaptability and flexibility	• Allowing buildings on small plots to be designed by different user groups within a flexible planning framework • Creating a discontinuous street network for motorised vehicles (traffic calming, streets that change direction, cul-de-sacs) • Providing a continuous, uninterrupted and prioritised circulation network for pedestrians and cyclists • Generating diversity at the neighbourhood scale through building typologies such as passive houses, plus-energy houses and (near) zero-energy buildings
5. Socio-spatial-material interaction	• Transformation of everyday social practices through the car-free living model (shared car use, public transport incentives, streets without on-street parking)

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- | | |
|---|--|
| | <ul style="list-style-type: none"> • Enhancement of social interaction through pedestrian- and bicycle-priority layouts • Community events operating in close integration with public spaces • Local initiatives in waste management forging links between community awareness and material cycles |
| 6. Multidimensional integration | <ul style="list-style-type: none"> • Co-design of mobility, energy, green infrastructure, and social programs • Urban form (the T-shaped spine) structured through the simultaneous organization of transport, landscape, and social amenities • Concurrent implementation of energy efficiency, housing affordability, and social diversity objectives • Integration of technical transitions (renewable energy, water management) with cultural and social transformation at the neighborhood scale |
| 7. Stakeholder participation and governance | <ul style="list-style-type: none"> • The evolution of the neighborhood form through a participatory approach over time • Support for affordable housing through the complete elimination of intermediary private developers • The central role of Forum Vauban in planning, consultancy, and neighborhood communication • Transparent governance carried out through neighborhood meetings, public events, and continuous information-sharing processes • Community-building activities that generate social cohesion: second-hand markets, festivals, workshops, and children's events |
| 8. Integration of local and global dynamics | <ul style="list-style-type: none"> • Reduction of energy dependency through the high share of on-site renewable energy generation • Preservation of the local water cycle • Enhanced resilience to global supply-chain disruptions through cooperative construction models and locally sourced building practices • Alignment with global carbon-reduction goals through a car-free lifestyle and short-distance urban structure • Positioning the neighborhood as a model for global urban sustainability debates through district-level circularity practices |

Critiques of the Circular Urban Design approach in Vauban

Although the Vauban District is widely celebrated in the literature as a comprehensive example of sustainability-oriented urban planning and development, several academic studies evaluate the project not only through its achievements but also through its social, spatial, and governance-related limitations (Fastenrath & Preller, 2018; Medved, 2018; Miller & Mössner, 2020). These critiques reveal that, despite presenting a model aligned with the principles of Circular Urban Design, Vauban's practices can generate unequal effects across different social groups, impose high costs or maintenance burdens in certain technical solutions, and allow participatory processes to be dominated by actors with higher levels of social capital (Fastenrath & Preller, 2018; Schwer, 2017; Medved, 2018; Miller & Mössner, 2020).

Table 4 systematically classifies these critiques under the eight core principles of Circular Urban Design, making Vauban's strengths as well as its constraints visible. In doing so, it

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presents an analytical framework that highlights the neighborhood's contestable aspects in terms of both practical applicability and socio-spatial equity (Fastenrath & Preller, 2018; Schwer, 2017; Medved, 2018; Miller & Mössner, 2020; Mössner, 2015; Mössner & Krueger, 2018).

Table 4. *Critical assessment of the Vauban District within the framework of Circular Urban Design (CUD) principles. Sources: Fastenrath & Preller, 2018; Schwer, 2017; Medved, 2018; Miller & Mössner, 2020; Mössner, 2015; Mössner & Krueger, 2018.*

CUD principle	Critiques of Vauban
1. Regeneration through natural processes	• The high maintenance costs of green infrastructure create challenges for long-term sustainability. • Green roofs and vertical gardens have been criticized in some buildings for their cost-performance ratio. • The overall impact of green roofs and vertical gardens on reducing the carbon footprint is considered limited.
2. Material circulation and resource management	• The quantitative impacts of construction-waste recycling have not been documented. • Passive house standards and photovoltaic technologies generate high levels of embodied carbon. • Material circularity relies on costly technologies, making it inaccessible for groups with low income. • Circularity remains confined to the neighbourhood scale and generates only limited impacts at the city scale.
3. Circulation and reuse of spaces	• Re-use practices have attracted predominantly upper–middle-class groups instead of fostering social diversity, generating a “green gentrification” effect. • The diversity of Baugruppen projects has weakened the aesthetic and morphological coherence of the neighbourhood.
4. Adaptability and flexibility	• Although the flexible street layout supports car-free living, it creates daily challenges for older adults, people with disabilities, and families with caregiving responsibilities. • Passive houses entail high long-term maintenance costs. • Participatory design processes are not accessible to everyone, as they require substantial time and knowledge.
5. Socio-spatial-material interaction	• The neighbourhood profile is shaped by groups with high social capital; class selectivity and green gentrification are frequently criticised. • Car-free living is challenging for households with caregiving responsibilities. • Car-sharing schemes are unevenly distributed, generating inequalities in mobility. • Community activities are dominated by specific social groups.
6. Multidimensional integration	• Although the technical and ecological integration is strong, the integration of social justice remains weak. • Multidimensional solutions are costly, and their scalability to other contexts is limited.
7. Stakeholder participation and governance	• Participation processes are criticised as a form of “participatory elitism,” as highly educated groups dominate the process. • Due to inequalities in access, participation is not open to all income groups.

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- The Baugruppen model is not accessible for migrants and households with low income.
 - The strong role of Forum Vauban creates institutional dependency.
8. Integration of local and global dynamics
- Vauban's success is closely tied to Germany's unique financial and governance infrastructure; it cannot be directly transferred to other cities.
 - Localised solutions have been found difficult to scale up in large metropolitan areas.
 - The specific contextual conditions of the neighbourhood model limit its applicability in different countries.

Conclusion

This study offers a comprehensive assessment of the applicability of circular design principles in residential areas through the case of the Vauban Eco-District in Freiburg, providing insights into sustainable urbanisation practices. Vauban developed a circular spatial strategy grounded in resource conservation by transforming an abandoned military site and refunctionalising existing land and infrastructure. Its small-plot structure and user-oriented Baugruppen model promoted cost and resource efficiency in housing production, while enhancing access to ownership and enabling social diversity. In terms of energy efficiency, the implementation of plus-energy houses, solar panels, and passive house standards has created a high-performance residential model. Meeting the neighbourhood's energy demand through renewable sources demonstrates that circular energy systems can be successfully implemented at the neighbourhood scale. Although a centralised water management system is absent, solutions such as rainwater harvesting, permeable surfaces, and green roofs have supported water circularity. Waste management has been primarily carried out through local initiatives; recycling stations and informational materials introduced during the construction phase helped raise awareness. However, the lack of quantitative data regarding the impacts of these practices highlights the need for future research to evaluate their long-term effectiveness.

In terms of mobility policies, Vauban stands as one of the pioneering examples of the “car-free lifestyle” model in Germany. With pedestrian- and bicycle-oriented transport infrastructure, car-sharing schemes, and tram integration, the district has achieved low-carbon mobility goals. This approach has yielded positive outcomes not only environmentally but also in terms of public health and quality of life. From the perspective of social sustainability, the Baugruppen construction model, the strong role of Forum Vauban in governance, social programmes, shared spaces, and alternative housing solutions for groups with low income have supported the development of an inclusive community structure. The integration of participatory planning processes into decision-making mechanisms has strengthened democratic legitimacy and contributed to a sense of local belonging.

In conclusion, the Vauban Eco-District presents an exemplary settlement model where circular design principles—covering building and infrastructure circularity, energy and water management, waste minimisation, mobility planning, social integration, and participatory governance—are holistically applied. Vauban illustrates that circular design must be addressed not only through technical and environmental solutions, but also through its socio-cultural and governance dimensions. Increasing the applicability of such integrated approaches in different geographical and social contexts requires further interdisciplinary and comparative research.

This study examines circular design practices solely through the example of the Vauban district and excludes the broader planning policies and other residential areas of Freiburg. The analysis is based on secondary data; primary data collection methods such as surveys or in-depth interviews were not employed. This limits the depth of analysis regarding the social

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impacts of the practices implemented. Nonetheless, the study provides a comprehensive example of how circular design can be holistically implemented at the neighbourhood scale. By presenting evaluations of the social, environmental, and governance dimensions of circular design, it establishes a foundation for future research in diverse contexts.

The Vauban Eco-District offers important policy lessons regarding the applicability of circular design principles in residential environments. Accordingly, the following recommendations may be relevant for local governments, planners, and decision-makers seeking to achieve sustainable urbanisation goals:

- Adaptive land use and the reuse of existing building stock should be prioritised as key policy areas for resource efficiency and reducing environmental impact. In planning new development areas, the transformation of abandoned or low-density urban sites should be emphasised.
- Collective housing production models (Baugruppen, cooperatives, etc.) promote social integration and limit the financialisation of housing, thereby enhancing affordability. Local governments should support such models through land allocation, financial incentives, and appropriate regulatory frameworks.
- Policies that support neighbourhood-scale renewable energy production enable on-site generation and contribute to energy circularity. Financial incentives, energy cooperatives, and technical support mechanisms should be expanded for low-carbon neighbourhoods.
- Transport strategies promoting car-free living reduce carbon emissions and enhance the public use of urban space. Pedestrian and cycling infrastructure should be integrated with public transport systems, and policies restricting private car use should be considered alongside urban design strategies.
- Institutionalising participatory planning processes is crucial for democratising decision-making. Civic initiatives should be supported, and appropriate legal and administrative frameworks must be established to incorporate local knowledge and needs into planning processes.

Although the Vauban Eco-District stands out as a pioneering example of circular design, it remains open to critique in several respects. The project was shaped primarily by environmentally conscious middle-class groups, limiting social inclusivity and housing affordability. The representativeness and influence of participatory planning processes remain unclear, particularly regarding the involvement of groups with low income in decision-making. Additionally, the high cost of technical solutions and the question of whether this model can be generalised to other geographical and socio-economic contexts remain debated. The lack of concrete, measurable data in areas such as waste and water management complicates the assessment of the project's long-term impacts. These limitations raise questions about the model's capacity to fully achieve holistic sustainability goals.

While the Vauban case offers a rich example of integrating circular design principles into residential environments, it also provides several potential directions for future research:

- Comparative case analyses are essential for assessing the applicability of circular design across different socio-economic and geographical contexts. More research is needed on how similar principles can be implemented in Global South cities.
- Quantitative, data-driven impact assessments will enable the measurement of long-term environmental, economic, and social outcomes of circular practices. Monitoring indicators such as energy efficiency, waste reduction, carbon emissions, and social cohesion will help guide policy-making processes.

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- Research on participatory governance models can shed light on the contribution, institutionalisation, and sustainability of local initiatives such as Forum Vauban.
- Studies examining the social impacts of spatial form and design strategies, especially those focusing on car-free living, age-friendly environments, and shared spaces, can be enriched through ethnographic approaches that explore everyday practices.
- The use of digital tools for monitoring and participation presents new opportunities for expanding circular design practices. Future research should explore innovative methods such as digital twins, participatory mapping, and online governance platforms.

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